

DISPLAY DIMENSIONALITY AND CONFLICT GEOMETRY EFFECTS ON MANEUVER PREFERENCES FOR RESOLVING IN-FLIGHT CONFLICTS

Lisa C Thomas
Boeing PhantomWorks
Seattle, WA

Christopher D Wickens
Institute of Aviation, University of Illinois
Savoy, IL

With the presence of a cockpit display of traffic information (CDTI) that provides graphical airspace information, pilots can use a variety of conflict resolution maneuvers in response to how they perceive the conflict. Inconsistent preference findings from previous research on conflict resolution using CDTIs may be due to inherent ambiguities in 3-D displays and/or a limited range of conflict geometries. This paper describes a study that investigates conflict resolution maneuver preferences using three displays with different frames of reference and a wide range of conflict geometries. Results indicate that 3-D displays with interactive viewpoints reduced spatial ambiguities. The interactive 3-D displays produced a preference for vertical maneuvers over lateral similar to a 2-D coplanar display; however this preference was reversed under increased workload conditions for both 3-D displays. Pilots in all three display conditions showed a preference to maneuver vertically away from intruders, though this was eliminated (or reversed) as workload increased. The 2-D coplanar display induced a preference to laterally turn away from approaching intruders, which overwhelmed a trained “turn right” preference.

INTRODUCTION

A cockpit display of traffic information (CDTI) is designed to show air traffic from the perspective of the pilot’s own aircraft (“ownship”; e.g. Johnson, Battiste, & Bochow, 1999). A generalized version of the CDTI has already been certified to fly by the FAA to aid in self-separation for in-flight following between ownship and other aircraft in the airspace. The FAA is currently in the process of developing criteria for certifying CDTIs to support more in-flight responsibilities, such as the detection and resolution of potential conflicts in the airspace (Thomas & Rantanen, in press).

A conflict is defined as the loss of the minimum required separation distance between two aircraft, defined in this study as 5 nautical miles lateral and \pm 1000 ft vertical; a resolution involves creating a new flight path that ensures that the two aircraft do not lose minimum separation. Traditionally, pilots and controllers are trained to resolve conflicts with lateral right turns (Federal Aviation Regulation 91.113, FAA/AIM, 2005). However, when pilots are given more flexibility to determine their own resolutions, they

demonstrate a wide variety of preferences (airspeed, heading, and altitude changes), which previous research has shown may be affected by the CDTI’s display dimensionality (2-D vs. 3-D) and the particular geometry of the conflict (for a summary, see Thomas & Wickens, 2005).

Display Dimensionality

Currently there are many options for displaying airspace information on all three spatial dimensions. One option for a CDTI display, 2-D coplanar, is to provide a top down map view of the airspace, and a second vertical situation view that provides a side or rear view. Another display option is to depict all three dimensions graphically in a 3-D display with a viewpoint typically set between 30°-60° above the horizon and either directly behind or slightly off to the side of ownship (e.g. Alexander, Wickens, & Merwin, 2004, Ellis et al, 1987).

Each of these display options (2-D, 3-D) has inherent perceptual and/or cognitive limitations that produce display/task tradeoffs, such as scanning and

integration costs (2-D) or line-of-sight ambiguity (3-D; Wickens & Hollands, 2000).

In terms of conflict resolution maneuver axis preference, the literature reveals a general preference for vertical over lateral maneuvers when pilots use CDTIs which provide a graphic representation of the vertical dimension (2-D Coplanar or 3-D). This vertical preference is amplified with an unambiguous graphic vertical representation such as the side/rear view of a 2-D Coplanar display (Alexander et al, 2004). Wickens, Helleberg, & Xu (2002) suggest that vertical maneuvers are preferred over lateral because they are less cognitively complex and are faster to implement than lateral, and resolve conflicts more quickly because the vertical component of the protected zone is much smaller (± 1000 ft) than the lateral (5 NM), and the control order is lower.

Conflict Geometry

Conflict geometry between two aircraft (ownship and intruder) can be defined by three parameters: 1) relative altitude and vertical speed, (2) airspeed of the intruder compared to ownship, and (3) the lateral angle formed by the intersection of the trajectories of the two aircraft. Conflict geometry has proven to affect conflict resolution strategies (e.g. Johnson, Bilimoria, Thomas, Lee, & Battiste, 2003). For example, pilots tend to resolve conflicts where the intruder is making a vertical change by choosing to maneuver vertically *toward* the intruder, and by climbing (vs. descending) if the intruder is flying level (Alexander et al 2004; Wickens et al, 2002). Pilots also show a tendency to turn laterally *toward* incoming intruders (Johnson et al, 2003), although this is not always the case, as Wickens et al (2002) found a small tendency to turn *away* from intruders.

Studies that have specifically contrasted 2-D planar or coplanar displays with 3-D perspective displays suggest that the dimensionality of the CDTI mediates the effect of conflict geometry on maneuver axis preference and safety (e.g. Alexander et al, 2004), although the pattern of interactions is not fully consistent across studies (Thomas & Wickens, 2005).

These prior studies comparing 3-D and 2-D displays have used single-viewpoint 3-D displays that were inherently ambiguous along the line-of-sight of the viewpoint. Hence, this may have led to a particular pattern of avoiding certain maneuvers to resolve conflicts with certain geometries where that 3-D ambiguity would compromise safety. In the current study, we address this by considering two different 3-D displays with interactive viewpoints which are intended to reduce ambiguity (Sollenberger & Milgram, 1993; Wickens & Helleberg, 1999). We expect that the

interactive viewpoints will reduce or even eliminate 3-D ambiguities, and produce maneuver preference patterns similar to that seen in the 2-D Coplanar condition, such as a comparable number of vertical maneuvers.

METHODS

Participants

Thirty student pilots (averaging 383 flight hours) from the University of Illinois participated in this study and were reimbursed for their participation.

Displays

There were three different CDTI formats. The Coplanar display (Figure 1) consisted of two side-by-side views of the airspace, one top-down (showing the horizontal plane) and one from the side (showing vertical information). The Toggle display (Figure 2) consisted of one display with two 3D viewpoint options that could be switched by pressing the “View 1/View 2” button on the CDTI button bar (located directly below the display).

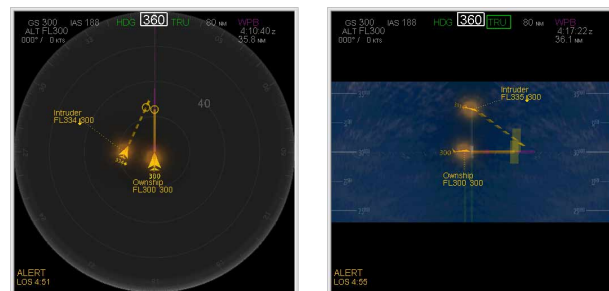


Figure 1. 2-D Coplanar display condition (both views displayed simultaneously).

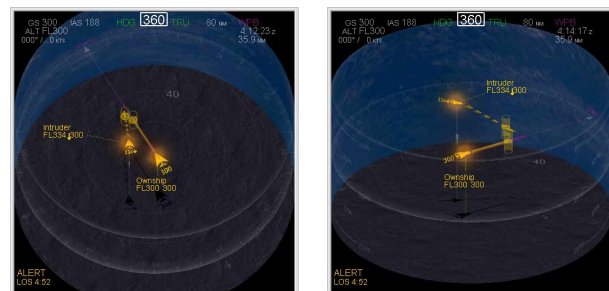


Figure 2. 3-D Toggle display views (displayed serially by clicking on a view-changing button).

The Manipulable display consisted of one display with a viewpoint, initially set to a 2-D top-down position, that could be moved by the participant using the mouse, from 0-90° vertically and through the entire 360° lateral range.

Design

Table 1 outlines 54 (or 3 x 3 x 3 x 2) unique conflict geometries (the within subject variables) which were used as the conflict trials. The total number of experimental trials was tripled by choosing three angles within each subset of conflict angles so that the three sets of conflicts were similar but not identical. The conflict geometries were defined by the intruder’s position relative to ownship, which was always flying a straight, level path. The same set of 162 trials were presented in a randomized orders to different pilots in each of the three display conditions.

Within Subjects Variables	Levels
Conflict Angle	Head-on: 120-180°, 180-240° Crossing: 60-120°, 240-300° Overtake: 0-60°, 300-360°
Altitude Change of Intruder	Ascending at 500 ft/min Level Descending at 500 ft/min
Relative Speed of Intruder	Faster: 1.5x OS speed Same as OS Slower: 2/3x OS speed

Table 1. Conflict geometry as described relative to ownship (OS) characteristics of airspeed, altitude, and distance. Note: Conflict angle is determined from the angle between the intruder’s heading compared to ownship’s heading at the point of conflict.

Procedure and Tasks

Pilots were randomly placed into one of the three display conditions. After signing consent forms, reading instructions, and performing practice trials, each pilot viewed 162 experimental trials depicting conflicts between ownship and an intruder. Each trial was constructed so that the conflict was predicted to occur in 5 minutes from the start of the trial. Pilots were instructed to resolve each of the conflicts by using the Route Altering Tool (RAT; Johnson et al, 2003) to create a new flight plath in one of three ways: laterally (by using the mouse to click and drag ownship’s flight path into a new configuration), and/or vertically (by using the mouse to click up/down arrows to change the destination altitude in the RAT pop-up menu). Feedback from the alerting color changes indicated whether a proposed resolution was successful: if it was, the color of the aircraft changed away from yellow. Once a successful resolution was created, pilots clicked an Enter and an Execute button, and after 5 seconds the next trial began. Although pilots could try any number and type of resolutions prior to entering one, only the final resolution was recorded for analysis.

RESULTS

Overall, resolution success was very high (94%) across all display conditions, and response times did not differ by display type.

Maneuver axis preference for each successful resolution was categorized as one of three types, based on the lateral and/or vertical deviations of the resolution flight path: lateral (e.g. left turn), vertical (e.g. climb), or dual-axis combination (e.g. climbing left turn) maneuvers. Maneuver axis preference was determined by proportion of each type of maneuver across successful trials in each conflict geometry category for each pilot. The maneuver axis preferences were analyzed by display condition and by each dimension of conflict geometry.

Display condition had no significant effect on maneuver preferences (refer to Figure 3, “Low workload” data). Overall, vertical maneuvers were chosen most often (40%, compared to 30% combination and 29% lateral); though the main effect was not statistically significant, whenever a significant preference emerged it was for vertical, while lateral maneuvers were never preferred. The vertical preference was observed across all display types for conflicts with approach angles of less than 120° (crossing and overtake conflicts; $F_{4, 104} = 13.06, p < 0.01$), for level conflicts ($F_{4, 104} = 3.36, p < 0.01$), and for faster-speed conflicts ($F_{4, 104} = 8.49, p < 0.01$).

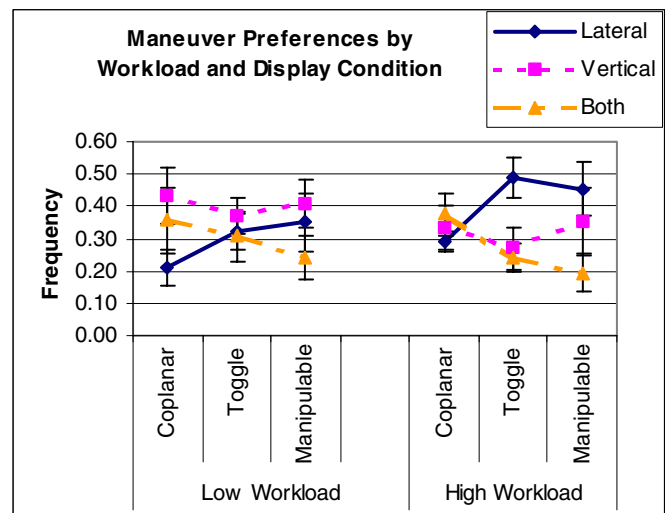


Figure 3. Maneuver preferences as a function of display condition, for low workload (current study) and high workload (follow-up study).

It should be noted that these vertical preferences were only observed under the low workload conditions of this experiment. A follow-up experiment (Thomas and Wickens, 2005, Experiment 2), which increased the task load by adding more traffic and a concurrent task, eliminated the vertical preference in the 2-D Coplanar

display, and produced preferences for lateral maneuvers in the two 3-D display conditions (“High Workload” data in Figure 3).

Maneuver axis preferences were further analyzed to determine whether there were preferences for maneuvering one direction or the other within the lateral or the vertical axis. Single-axis vertical direction preferences (ascents vs. descents) were evaluated on the basis of the intruder’s vertical behavior (ascending or descending only; cases where intruder was flying level were analyzed separately). When using vertical maneuvers, pilots exhibited a preference to maneuver vertically away from the intruder across all display conditions ($F_{1, 26} = 50.4, p < 0.01$). It must be noted that this result was only evident in this low workload conditions that characterize this experiment; results from a subsequent experiment with increased task load revealed that the vertical “maneuver away” preference was eliminated for the 2-D Coplanar display and reversed for both 3-D displays.

Vertical direction preferences when the intruder was flying level revealed a marginally significant effect ($F_{2, 52} = 2.84, p = 0.07$), where ascents were most preferred (45%), followed by level flight (31%) and then by descents (25%). Neither the display condition nor any dimension of conflict geometry had a significant effect on vertical direction preference.

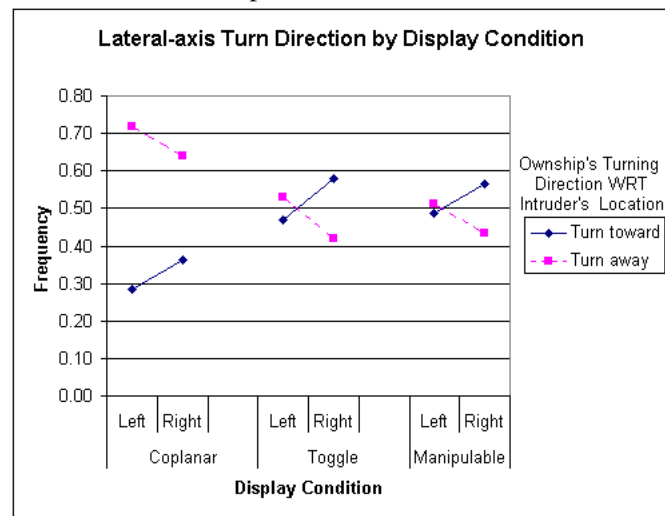


Figure 4. Breakdown of lateral-axis turning preference by left-right and by whether the maneuver was toward or away from the intruder.

Within the lateral axis, significant tendency to maneuver laterally away from intruders ($F_{2, 52} = 4.85, p < 0.01$) was only evident in the 2-D Coplanar condition (refer to Figure 4). (Results from the subsequent increased task load experiment revealed that both 3-D displays showed the same turn-away preference as the 2-D Coplanar display.)

Further analysis also revealed a significant overall tendency to maneuver right-ward (55% of the time; $F_{1, 52} = 12.38, p < 0.01$), though this right-ward preference did not interact with display condition ($F_{2, 52} = 0.29, p > 0.20$). The tendency to turn right was overwhelmed by the stronger tendency to turn away in the 2-D Coplanar condition (see Figure 4). Overtake angle conflicts produced a greater preference for turning away than toward the intruder ($F_{2, 52} = 20.04, p < 0.001$).

DISCUSSION

Resolution performance results (success rates and response times) indicated that all three displays produced equivalent performance, suggesting that the viewpoint altering features on both 3-D displays were sufficient to reduce spatial ambiguities (further described in Thomas & Wickens, 2005, Exp 1). Similarly, display dimensionality had no significant effect on maneuver axis preference, most likely due to the absence of dimensional ambiguities which may otherwise have produced differential maneuver preferences.

Each conflict geometry dimension, however, had an effect on maneuver axis preference. Vertical maneuvers were preferred over lateral and combination in decreasing angle conflicts, when the intruder was flying level, or as intruder’s relative speed increased. In all cases, vertical maneuvers were most likely preferred because of the ease and quickness with which they could resolve the conflict (see also Wickens, Helleberg, & Xu, 2002), specifically when lateral maneuvers were limited (in the case of smaller-angle approaches; Johnson et al, 2003), when altitude change of the intruder was not an issue (level-flight conflicts), and when the closure rate was relatively fast (increasing speed conflicts).

However, when workload was increased, the vertical preference noted above was eliminated for the 2-D Coplanar display, and reversed for both 3-D displays, which actually showed a preference for lateral maneuvers. Increased task load was also found to reduce the amount of viewpoint interactivity (Thomas and Wickens, 2005), suggesting that spatial ambiguities were not eliminated under high workload conditions and may have played a role in maneuver choice. It may be that higher workload combined with unresolved spatial ambiguities induces an adaptive tendency to maneuver the aircraft in a way that preserves a more stable state (level), than the climbing or descending state, both of which have airspeed and possible stalling implications and which involve spatial processing in the third dimension.

Preferences for maneuver directions within the vertical axis are also modified by workload level. In low workload (single task) conditions such as the current

experiment, a strong preference to maneuver away from the intruder emerges across all display types. However, high workload (dual task) reduces and even reverses this preference, and the effect is display-dependent. This again suggests that unresolved ambiguities resulting from reduced viewpoint interactivity influence vertical maneuvering direction.

Across both workload levels, ascents were preferred over descents when both aircraft were flying level, replicating another common finding from previous studies (Alexander et al, 2004; Wickens et al, 2002).

For direction preference within the lateral flight axis, only the 2-D Coplanar display induced a strong preference to laterally turn *away* from an approaching intruder, replicating a finding from Wickens et al (2002). The two 3-D displays showed no lateral axis direction preference at all in the low workload conditions of this experiment, but did exhibit a turn-away preference under increased workload conditions. The reasons for the turn away preference are not clear: in most cases the most efficient maneuver is to turn toward the intruder (Johnson et al, 2003).

One potential limitation of this research is the generalizability of findings from a simplified single-task desktop CDTI simulation to a more realistic in-flight environment where the CDTI is one of many displays all requiring attention from the pilot. This limitation was addressed in a subsequent experiment, described in Thomas & Wickens (2005; Exp 2), which increased the task load and the number of traffic aircraft in the airspace. As noted, results from this subsequent experiment indicated that increased task load had significant effects on maneuver preferences.

CONCLUSIONS

Most importantly, the 3-D displays' interactive viewpoints successfully reduced spatial ambiguities and produced performance levels and maneuver preferences very similar to those observed in the 2-D Coplanar condition. When clear maneuver axis preferences were observed, vertical maneuvers were preferred over lateral, a finding that supports previous research. Pilots preferred climbs over descents when the intruder was flying level, replicating previous research. However, both lateral and vertical turning preferences were significantly modified by increased workload, especially for the two 3-D displays.

ACKNOWLEDGMENTS

This research was sponsored by NASA Ames Research Center #NAG 2-1535. Dr. David Foyle was

the technical monitor. The authors also thank Dr. Walt Johnson and Dr. Sandy Hart for their contributions, and Dominic Wong, George Lawton, and Sharon Yeakel for their software development expertise.

REFERENCES

- Alexander, A. L., Wickens, C. D., & Merwin, D. H. (2004). Perspective and coplanar cockpit displays of traffic information: Implications for maneuver choice, flight safety, and mental workload. *International Journal of Aviation Psychology*, 15, 1-21.
- Ellis, SR, McGreevy, MW, & Hitchcock, RJ. (1987) Perspective traffic display format and airline pilot traffic avoidance. *Human Factors*, 29, 371-382.
- Johnson, WW, Battiste, V, & Bochow, S. (1999) A cockpit display designed to enable limited flight deck separation responsibility. *1999 WAC Proceedings*. Anaheim, CA.
- Johnson, WW, Bilimoria, KD, Thomas, LC, Lee, HQ, & Battiste, V. (2003) Comparison of human and automation generated conflict resolutions. *AIAA GNC Conference, August 2003*.
- Thomas, L. C., & Rantanen, E. M. (in press). Human factors issues in implementation of advanced aviation technologies: A case of false alerts and cockpit displays of traffic information. *Theoretical Issues of Ergonomics Science*.
- Sollenberger, R. & Milgram, P. (1993) Effects of stereoscopic and rotational displays in a three-dimensional path-tracing task. *Human Factors*, 26(1), 33-48.
- Thomas, L.C., & Wickens, C.D. (2005) Effects of display dimensionality, conflict geometry, and time pressure on conflict detection and resolution performance using a cockpit display of traffic information. *Aviation Human Factors Division Technical Report*.
- Wickens, CD, & Helleberg, J. (1999) Interactive perspective displays for airborne hazard awareness. *Aviation Human Factors Division Technical Report ARL-99-1/ROCKWELL-99-1*.
- Wickens, CD, Helleberg, J, & Xu, X. (2002) Pilot maneuver choice and workload in free flight. *Human Factors*, 44(2), 171-188.
- Wickens, C.D., & Hollands, J. (2000) *Engineering psychology and human performance*, 3rd Ed. New York: Prentice Hall.